

Electron Impact on Atmospheric Gases

2. Yield Spectra

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We introduce a concept 'yield spectrum' and calculate this two-dimensional function using a modified discrete energy bin method for 50-eV to 10-keV incident electrons impacting on the gases Ar, H₂, H₂O, O₂, N₂, O, CO, CO₂, and He. The yield spectrum is amenable to physical interpretation, accurate analytic representation, and convenient application to the determination of all types of yields needed in aeronomical problems.

INTRODUCTION

The successful acquisition of ultraviolet rocket spectra of auroral events and of the dayglow in the early 1960's [Crosswhite *et al.*, 1962] generated a need for detailed calculations of upper atmospheric spectra. In response to this need, Green and Barth [1965] initiated a microscopic approach to the electron energy deposition problem (see also Green and Dutta [1967] and associated papers) which has proven quite fruitful in explaining many features of auroral and dayglow spectra. The deposition aspects of this approach involve two major tasks: first, the assembly of comprehensive sets of cross sections for excitation, ionization, and dissociation of the involved atmospheric species by electrons and, second, the use of an energy apportionment method to distribute the electron energy among the various loss processes.

In this paper we concern ourselves with this second task of distributing the electron energy among the various loss processes. One of the very first methods chosen by the University of Florida Aeronomy Group in resolving the energy degradation problem was an adaptation of the continuous slowing down approximation (CSDA) first used by Niels Bohr [1913, 1915]. This method is subject to error when the energy losses are a substantial fraction of the primary energy [Peterson, 1969]. These errors were generally of minor consequence in comparison to the inaccuracies associated with the available cross section sets. However, as accurate cross section data for the atmospheric gases have become available, it has become purposeful to utilize a more accurate energy apportionment methodology for aeronomy.

One such method is the discrete energy bin method (DEB) of Peterson [1969]. In this approach the energy range between some initial value and the threshold of the state of interest is divided into bins. An idealized degradation process is then

assumed to commence in which the initial electron is fractionally redistributed into the lower-energy bins. This idealized process is continued as each energy bin is emptied in turn until all the bins above and including the bin containing the lowest threshold have been emptied. In this way the mean total number of excitations of each state produced in the complete degradation of an electron from a given incident energy is obtained.

In the modification of the DEB method introduced by Jura [1971], Dalgarno and Lejeune [1971], and Cravens *et al.* [1975] the equilibrium flux or degradation spectrum $f(E, E_0)$ of Spencer and Fano [1954] is obtained directly. Schneider and Cormack [1959] and Klotz and Wright [1970] in a similar manner obtained the $f(E, E_0)$ using Monte Carlo techniques. Attempts have been made to find the systematics of degradation spectra for use in applications. First, Douthat [1975a] found that the quantity $f(E, E_0)\sigma_i(E)(E/E_0) \times \ln(E_0/I)$ scaled approximately when plotted against $z = \ln(E/I)/\ln(E_0/I)$ for helium. Second, Garvey *et al.* [1977a] found an analytic function for $f(E, E_0)$ that worked quite well for H₂ with electrons having incident energies from 50 eV to 50 keV. However, this analytic function is fairly cumbersome, and our studies with other gases indicate that the degradation spectra are usually more complex than for H₂. The present work was motivated in part by a desire to simplify applications of what is essentially the equilibrium flux or the degradation spectrum. In addition, we sought to have a basic distribution function whose physical implications are more transparent than are the implications of the equilibrium flux or degradation spectra [Fano and Spencer, 1975].

YIELD SPECTRA

In the present work we use the DEB method but focus our attention not upon the equilibrium flux or degradation spectra

TABLE 1. Parameters for the Yield Spectrum, (4), for Nine Atmospheric Gases

Gas	$100A_1$	A_2	I	t	r	s
Ar	2.480	0.954	15.76	0.0	0.0	-0.0878
H ₂	3.847	0.706	16.00	0.01	0.0	-0.0215
H ₂ O	2.726	1.450	12.62	-0.01	0.0	-0.0828
O ₂	1.718	1.576	12.10	0.01	-0.02	-0.0700
N ₂	2.265	0.964	15.58	0.0	0.02	-0.0518
O	1.998	1.537	13.60	-0.02	0.08	-0.0730
CO	2.661	1.188	14.01	0.0	0.02	-0.0300
CO ₂	2.173	1.411	13.76	0.0	0.0	-0.0536
He	1.810	0.377	24.58	0.01	0.0	-0.0268

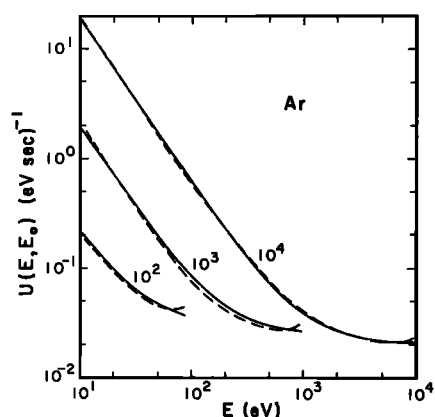


Fig. 1a.

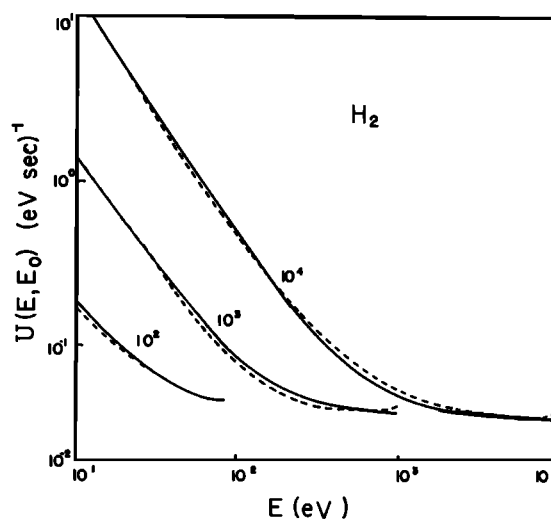


Fig. 1b.

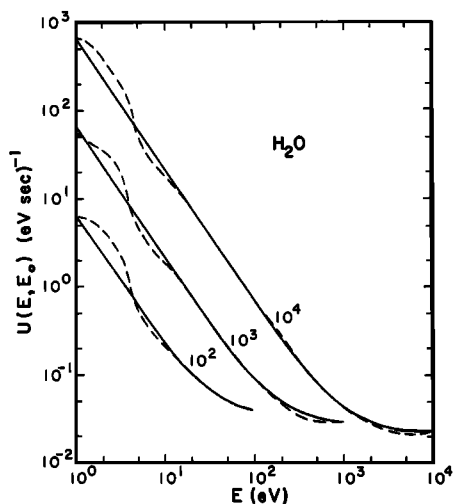


Fig. 1c.

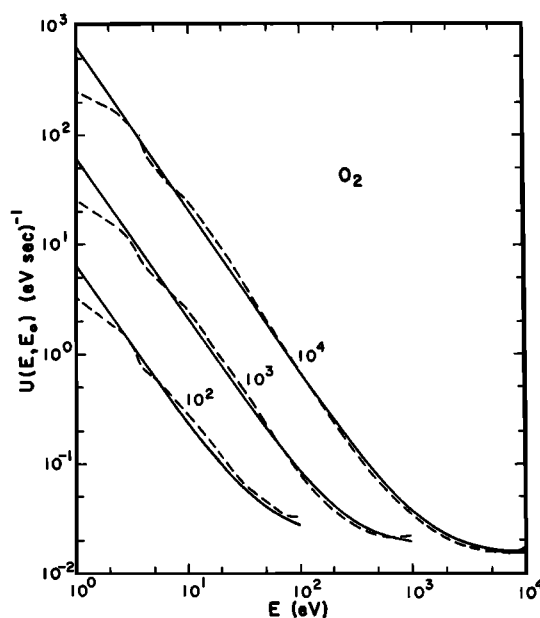


Fig. 1d.

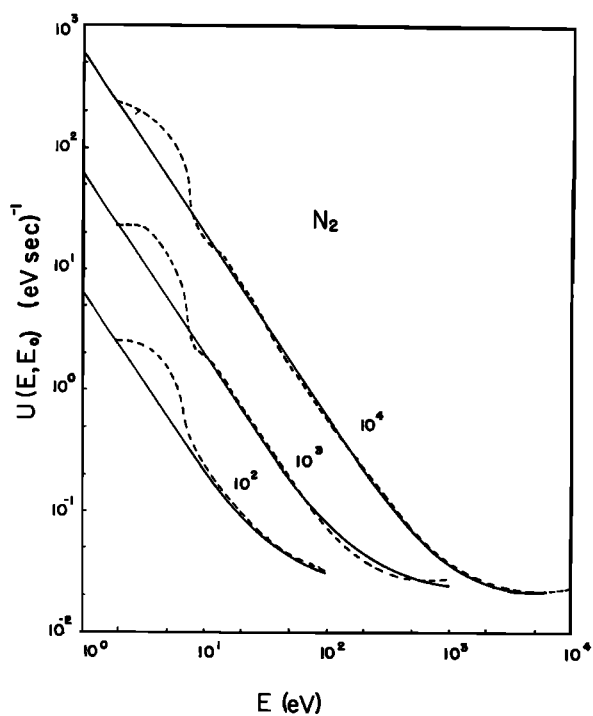


Fig. 1e.

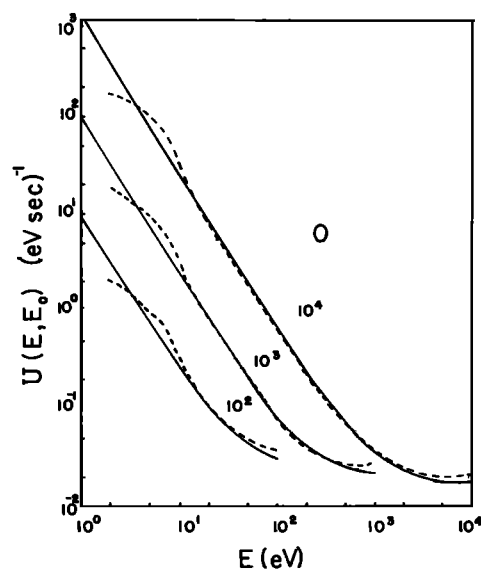


Fig. 1f.

Fig. 1. Yield spectra $U(E, E_0)$ from the MDEB method (dashed lines) and from (4) (solid lines) for (a) Ar, (b) H_2 , (c) H_2O , (d) O_2 , (e) N_2 , (f) O, (g) CO, (h) CO_2 , and (i) He at three incident energies, 10^2 , 10^3 , and 10^4 eV. We cut off the yield spectra from the MDEB at the lowest threshold of the gas.

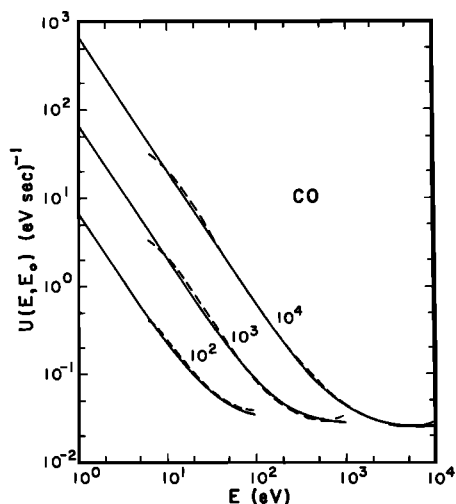


Fig. 1g.

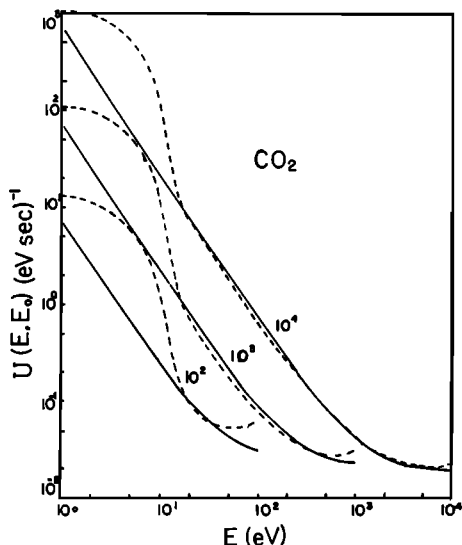


Fig. 1h.

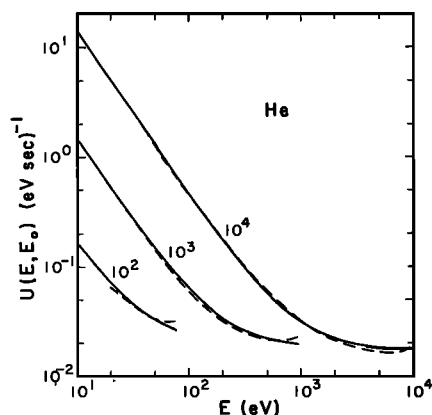


Fig. 1i.

TABLE 2. Parameters for the Total Inelastic Cross Section of Ar, H₂, and He for Use With (5)

Gas	F_T	W_T	α	β	Ω
Ar	0.1565	11.80	0.418	2.28	0.915
H ₂	0.4028	2.25	0.445	6.37	0.972
He	0.0277	19.70	0.229	1.66	0.955

but rather upon the 'yield spectra' given by

$$U(E, E_0) = \sigma_T(E)f(E, E_0) = N(E)/\Delta E \quad (1)$$

Here, $\sigma_T(E)$ is the total inelastic cross section, and $N(E)$ is the number of electrons in the bin centered at E after one bin has been emptied and before the next lower nonempty bin of width ΔE centered at E is considered. We thus utilize the DEB method in the mode of Jura [1971] rather than that of Peterson. In addition, we utilize a technique of Garvey *et al.* [1977b] (hereafter referred to as GPGb) which permits the use of wider bin widths. This greatly reduces the time and cost of the DEB method and permits extension of the method to high energies. We will refer to the DEB method, as modified by Jura and GPGb and as used to obtain yield spectra, as the modified discrete energy bin (MDEB) method.

The yield spectrum embodies the non-spatial information of the degradation process. It may be used to calculate the yield of any state by means of the equation

$$J_j(E_0) = \int_{W_j}^{E_0} U(E, E_0)p_j(E) dE \quad (2)$$

where $p_j(E) = \sigma_j(E)/\sigma_T(E)$ is the probability for excitation of the j th state with excitation energy W_j . This equation follows directly from the corresponding equation for populations in terms of the degradation spectrum and the cross sections $\sigma_j(E)$. While the transformation to (2) is trivial, the advantages of working with yield spectra and probability of excitation rather than degradation spectra and cross sections are quite substantial. Thus, except at very low energies, $U(E, E_0)$ and $p_j(E)$ both vary with E in a much simpler manner than do $f(E, E_0)$ and $\sigma_j(E)$. Hence the numerical evaluation of (2) is more efficient than the corresponding equation based upon degradation spectra. Indeed, at high energies $U(E, E_0)$ becomes very flat as does $p_j(E)$ for allowed states of excitation. Thus from the gross form of (2) we would expect the integral to approach

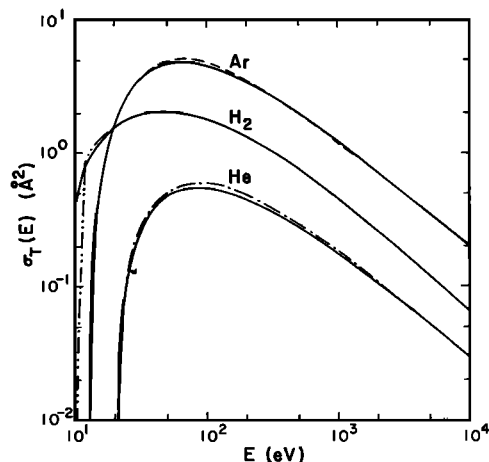


Fig. 2. Total inelastic electron impact cross sections for Ar (dashed line), H₂ (double-dot-dashed line), and He (dot-dashed line) with their analytic fits (solid lines) using (5).

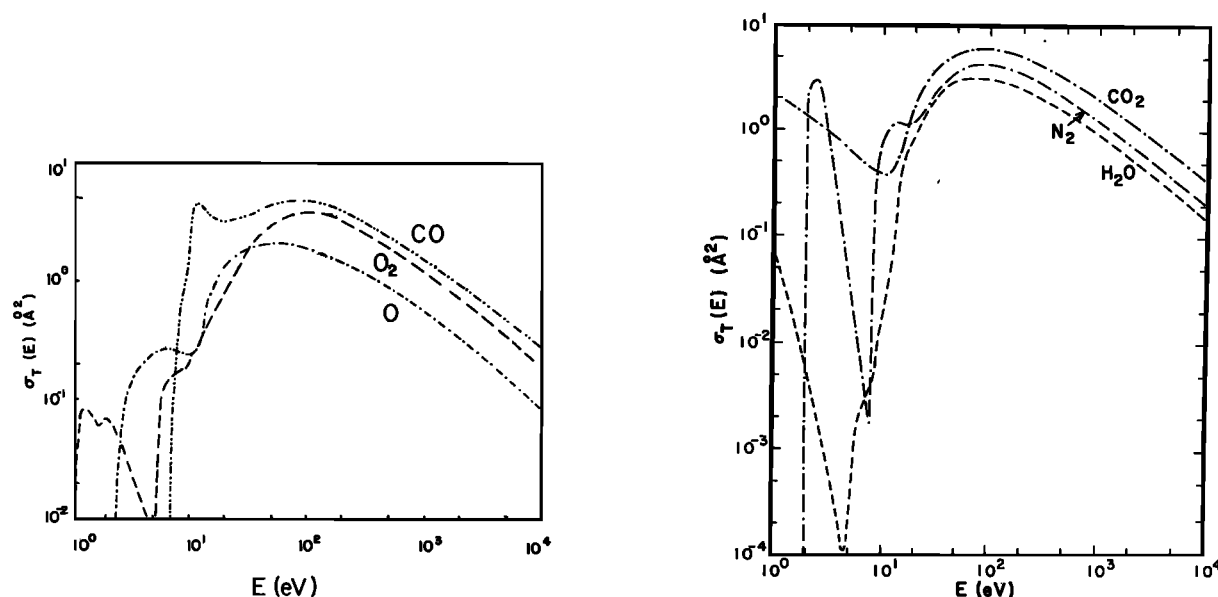


Fig. 3. Total inelastic electron impact cross sections for (a) CO, O₂, and O and (b) CO₂, N₂, and H₂O.

a constant times E_0 . Hence a specific yield $J_i(E_0)/E_0$ should approach a constant at higher primary energies. The same remarks apply to specific yields for ionization and dissociation. Since for forbidden states the probability rises and then falls rapidly at higher energies, the resulting yields are somewhat more complicated than for allowed states. We will discuss what to expect after we have introduced an approximate analytic representation of yield spectra.

ANALYTIC SPECTRAL YIELDS

Because of the simple nature of the $U(E, E_0)$ it is natural to continue a philosophy of analytic representation [see Green and Barth, 1965; Green and Dutta, 1967; Green and Stolarski, 1966] even though we are now going beyond the continuous slowing down approximation by allowing for the quantum nature of the slowing down process. The analytic properties of $U(E, E_0)$ will permit us to infer important derived properties of gases with a degree of accuracy which should suffice for many aeronautical applications.

We use the revised cross sections of O₂, N₂, O, CO, CO₂, and He from Jackman *et al.* [1977] (hereafter referred to as JGG), Ar cross sections from Peterson and Allen [1972], H₂ cross sections from GPGB, and H₂O cross sections from Olivero *et al.* [1972]. With these cross sections we can use the MDEB calculation method to find numerical $U(E, E_0)$ of any of the

nine atmospheric gases for any energy. We have calculated these spectra for a range of incident energies E_0 from 50 eV to 10 keV. For the purposes of many applications it is useful to represent the yield spectra by

$$U(E, E_0) = U_a(E, E_0)\theta(E_0 - E - E_\theta) + \delta(E_0 - E) \quad (3)$$

Here, θ is the Heaviside function with E_θ , the minimum threshold of the states considered, $\delta(E_0 - E)$ is the Dirac delta function which allows for the contribution of the source itself, and $U_a(E, E_0)$ can be approximately represented by

$$U_a(E, E_0) = A_1\xi_0^s + A_2(\xi_0^{1-t}/\epsilon^{s/2+r}) \quad (4)$$

where A_1 and A_2 are the principal parameters, r , s , and t are small parameters, $\xi_0 = E_0/1000$, and $\epsilon = E/I$ (I is equal to the lowest ionization threshold). The parameters for the various gases found through a nonlinear least square fitting procedure are given in Table 1. Qualitatively, the first term in (4) arises from primaries and the second term from secondary and higher generations.

In Figures 1a–1i we present yield spectra obtained using the MDEB method for all of the nine gases at 10²-, 10³-, and 10⁴-eV primary energies. Also shown are the corresponding analytic fits using (4). The plotted $U(E, E_0)$ from the MDEB were smoothed for energies E close to E_0 , so that we do not explic-

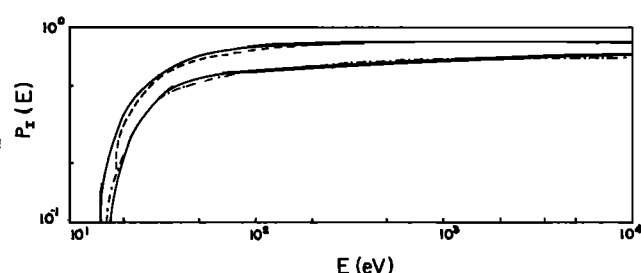


Fig. 4. Ionization probabilities $p_i(E)$ for O (dashed line) and CO₂ (dot-dashed line) with their analytic fits (solid lines) using (8).

TABLE 3. Parameters for the Ionization Probability for Use in (8)

Species	C	α	ν	u
Ar	0.805	3.0	1.0	0.0
H ₂	0.512	2.16	1.0	0.0
H ₂ O	0.718	1.75	1.0	0.0175
O ₂	0.987	1.22	2.0	0.0322
N ₂	0.938	0.87	1.0	0.0525
O	0.851	1.41	1.0	0.0
CO	0.789	1.52	2.0	0.0322
CO ₂	0.549	2.69	2.0	-0.0478
He	0.705	2.77	1.0	0.0

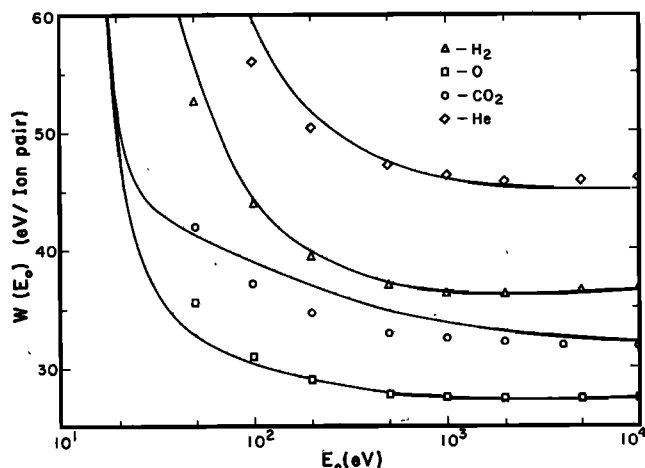


Fig. 5. W , energy per ion pair, for four gases, H_2 , O, CO_2 , and He, as calculated by the MDEB method. The solid lines indicate our analytic fit found from the reciprocal of (9).

itly show the fine structure (identified as the Lewis effect by Douthat [1975a, b]).

If the probability for exciting a state $p_j(E)$ were representable as a sum of powers of E , we could use (2) to obtain an analytic result for $J_i(E_0)$. Unfortunately, the probability $p_j(E)$ for excitation of any j th state usually has a complex behavior at low energies due to the denominator $\sigma_T(E)$ and hence is difficult to represent analytically. We are, however, able to represent the total inelastic cross section $\sigma_T(E)$ for three gases (Ar, H_2 , and He) by a fairly simple expression:

$$\sigma_T(E) = q_0 F_T [1 - (W_T/E)^\alpha]^\beta (W_T/E)^\Omega \quad (5)$$

Here, $q_0 = 6.513 \times 10^{-14} \text{ eV}^2 \text{ cm}^2$, F_T is the amplitude factor, W_T is a fitting parameter that is usually close to the lowest threshold of the specie and α , β , and Ω are three other adjustable parameters. We present the parameters for Ar, H_2 , and He in Table 2. The total inelastic cross section and the fits obtained for these three gases are given in Figure 2.

The cross sections for the other six gases are shown in Figures 3a and 3b. Here the $\sigma_T(E)$ can be represented by a simple summation

$$\sigma_T(E) = \sum_j \sigma_j(E) + \sum_i \sigma_i(E) \quad (6)$$

where $\sigma_i(E)$ is the i th ionization state cross section and $\sigma_j(E)$ is

the j th excitation state cross section. In all nine cases we can represent the probability for ionization

$$p_i(E) = \sum_j \sigma_j(E)/\sigma_T(E) \quad (7)$$

by an analytic form similar to (5) given by

$$p_i(E) = C [1 - \epsilon^{-\alpha}]^\nu \epsilon^{-\alpha} \quad (8)$$

Figure 4 illustrated such fits for the cases of O and CO_2 . The parameters for $p_i(E)$ of all nine gases are given in Table 3. For the present application it has the further advantage that when ν is a small integer (it is 1 or 2 for all nine gases), the specific ion yield may be evaluated analytically.

The specific ion yield is calculated with

$$J_i(E_0) = E_0^{-1} \int_1^{E_0} U(E, E_0) p_i(E) dE \quad (9)$$

Substituting the expression for $U(E, E_0)$, (3), and the expression for $p_i(E)$, (8), into (9), we can obtain an analytic expression for $J_i(E_0)$. The reciprocal of $J_i(E_0)$ is the energy per ion pair W , which we find to be approximately constant for $E_0 \gg 1$. Figure 5 shows the analytic W function so obtained along with values of W generated by using the numerical MDEB method for four gases (namely H_2 , O, CO_2 , and He). In Table 4 we give the W results obtained using (9), CSDA (with the Peterson and Green [1968] method), and the numerical MDEB method. Also given are the W values from experiments for eight of the gases found in Christophoru [1971]. Experimental values of W are not available for atomic oxygen.

DISCUSSION OF THE YIELD SPECTRUM AND POPULATIONS OF STATES

The yield spectra $U(E, E_0)$, in addition to providing an analytic ion yield, can also be used to find the population of any given excitation or ionization state with the use of (2). For those states with thresholds above 8 eV the populations we obtain using the analytic yield spectra in (4) are usually within a few percent of the direct results of the DEB calculations. In Table 5 we give a short illustration of populations for two states of each gas whose cross sections behaved differently as functions of energy. We show in Table 5 the DEB method population, the population resulting from the analytic yield spectra (AYS), and the percentage difference (PD) between the two calculations.

The three gases with the simplest electronic structure, namely, H_2 , He, and Ar, have their $U(E, E_0)$ represented quite well by the analytic form, and the populations for most states at most energies are good to 3% of the DEB calculations.

TABLE 4. W (Energy per Ion Pair) at

Species	$E_0 = 50 \text{ eV}$			$E_0 = 100 \text{ eV}$			$E_0 = 200 \text{ eV}$			$E_0 = 500 \text{ eV}$		
	MDEB	CSDA	AF	MDEB	CSDA	AF	MDEB	CSDA	AF	MDEB	CSDA	AF
Ar	33.9	42.2	34.1	29.7	33.5	29.0	27.9	30.7	27.2	27.1	29.2	26.5
H_2	52.6	67.4	55.6	43.8	49.3	44.4	39.4	42.1	39.8	36.9	39.0	37.3
H_2O	33.1	38.8	30.4	30.8	34.8	29.0	29.3	32.5	28.3	28.2	30.8	28.0
O_2	38.8	48.3	41.2	34.0	37.6	36.0	32.1	34.8	33.3	31.2	33.3	31.4
N_2	48.1	58.0	45.3	40.1	42.6	39.6	37.0	38.3	36.6	35.6	36.3	34.6
O	35.6	44.9	32.8	30.9	35.0	30.4	28.8	31.8	29.0	27.7	30.0	27.9
CO	49.2	58.2	51.0	39.3	41.6	40.5	35.6	36.7	35.9	33.9	34.4	33.2
CO_2	42.0	52.3	42.0	37.2	42.1	39.0	34.7	38.2	36.9	32.9	35.7	34.9
He	72.2	116.	78.0	56.0	66.9	59.6	50.3	56.2	51.7	47.2	51.2	47.4

The three columns per incident energy give the results from separate ways of calculating W . The final column Chr gives experimental W for Christophoru [1971].

There are, of course, deviations from these good fits, but we can say that above a primary energy of 100 eV the analytic yield spectra results for these three gases are within 9% of the DEB values for all states. The gases CO₂ and H₂O are represented quite well above their vibrational levels by the analytic $U(E, E_0)$. Even the vibrational populations for these gases are found to be within 20%. This is illustrated by the $(A_1)_v$ state of H₂O in Table 5. At all energies the AYS values are within 16% of the DEB populations.

The other gases, N₂, O₂, O, and CO, have yield spectra with a more intricate structure at energies below 10 eV. We have found the electronic allowed excitation state populations from our analytic $U(E, E_0)$ to be within several percent (3–12%) of the DEB values. The electronic forbidden and vibrational state populations are within 25% of the DEB method populations. We notice in Table 5 that the analytic yield spectra give quite good populations, especially at the higher energies. Although we have included only two states from each gas and checked only a few other key states in each gas, we are confident that these states are representative of these atmospheric gases. Thus the table reflects the general accuracy, convenience, and limitation of our analytic yield spectra for most aeronautical needs.

Our results via the AYS route could be improved for the states with thresholds below 8 eV if we use more detailed analytic representation of yield spectra. However, the advantages over numerical yield spectra obtained from our MDEB method would become much smaller, so that it would usually be just as well to numerically integrate (2) to obtain the desired yields.

CONCLUSION

We have used the cross sections presented by JGG to calculate the 'yield spectra' for the gases Ar, H₂, H₂O, O₂, N₂, O, CO, CO₂, and He. In addition, we have developed a fairly simple analytic expression to represent these spectra. For the range of incident energies between 50 eV and 10 keV we can fit the calculated yield spectra quite well (typically to within several percent) with a five-parameter analytic equation.

We have also found in a few spot checks on each gas that this $U(E, E_0)$ gives populations for most states with thresholds above 8 eV quite accurately when compared with the DEB calculations. Other lower threshold state populations can be found, but their values are not as precise. They can, however, be used for calculations not requiring accuracy better than 25%. While we have not yet calculated the yield spectra for gaseous mixtures, from the similarity in shape and magnitudes

of the yield spectra for all of the gases studied we would expect that the yield spectra for mixtures would be some reasonable weighted average of the component yield spectra. A few runs through the MDEB program to generate numerical yield spectra together with a two-dimensional nonlinear least square parameter fitting program should readily establish the yield spectra parameters for any mixture needed.

In conclusion, we might note that the gross characteristics of all yield spectra appear to be well described by the two-parameter function $U_a(E, E_0) = A_1 + A_2 \xi_0 \epsilon^{-3/2}$ which we obtain by setting r , s , and t in (4) to zero. Since the gross characteristics of all allowed excitation, dissociation, and ionization probabilities are of the form $p = C[1 - \epsilon^{-\alpha}]$ (we set $\nu = 1$ and $u = 0$ in (8)), simple integration of (2) in conjunction with (3) shows explicitly that the specific yields approximately approach the constant

$$J_a = A_1 C + A_2 C I / 1000 (\frac{1}{2}) (\alpha + \frac{1}{2}) \quad (10)$$

In actuality, the small parameters are consequential for quantitative work, but (10) gives the overall magnitude.

For forbidden states, we may set $\nu = 1$, but let $u > 0$. In this case the same elementary integration indicates that the specific yield will be large at low energies but will settle down to a small constant at high energies. The energy per ion pair W , obtained by using the five-parameter analytic representation of the yield spectra and the four-parameter analytic form for the probability for ionization is within a few percent for all gases from 1 keV to 10 keV. Work which we have carried out on relativistic (up to 10 MeV) electrons impacting upon H₂ suggests that the general features of our yield spectra and the resultant specific yields will be approximately maintained even at much higher energies than those considered in this study.

Studies of ion yields go back to Roentgen, Becquerel, Thompson, Bragg, Rutherford, Bohr, and other founders of modern physics. From these and subsequent studies a general acceptance of the approximate constancy of specific ion yields and its reciprocal, the energy per ion pair, has evolved. However, despite an intensive search of the literature, we have found no previous quantitative explanation of the behavior of specific ion yields in terms of detailed atomic properties. In this work the general behavior of the ion yield and particularly its approximate constancy at high energies follow directly from the general properties of yield spectra and ionization probabilities. It is gratifying to us that in attempting to address some specific aeronautical problems we may have shed some light on one of the oldest problems in modern physics.

Eight Incident Energies for Nine Gases

$E_0 = 1000$ eV			$E_0 = 2000$ eV			$E_0 = 5000$ eV			$E_0 = 10,000$ eV			Chr
MDEB	CSDA	AF	MDEB	CSDA	AF	MDEB	CSDA	AF	MDEB	CSDA	AF	
27.1	29.1	26.5	27.2	29.2	26.7	27.4	29.3	27.2	27.5	29.5	27.7	26.4
36.3	38.0	36.5	36.2	37.8	36.2	36.5	38.0	36.2	36.8	38.3	36.4	36.4
27.8	30.2	28.1	27.8	30.0	28.4	28.0	29.8	29.0	29.6	29.8	29.5	30.5
30.9	33.0	30.8	31.0	32.9	30.7	31.1	32.7	31.0	31.3	32.7	31.5	32.2
35.3	36.0	34.0	35.4	35.9	34.1	35.8	35.9	34.7	36.0	36.0	35.4	36.4
27.4	29.5	27.5	27.3	29.4	27.3	27.3	29.3	27.3	27.4	29.3	27.4	...
33.5	33.9	32.4	33.4	33.8	32.2	33.6	33.8	32.4	33.8	34.1	32.8	34.7
32.5	34.9	33.9	32.1	34.4	33.1	31.8	33.9	32.4	31.7	33.8	32.0	34.3
46.3	49.8	46.0	45.8	49.2	45.3	45.8	48.9	45.0	46.0	48.9	45.1	46.0

eight gases. MDEB is the modified discrete energy bin; CSDA, continuous slowing down approximation; AF, analytic fit; and Chr,

TABLE 5. Comparison of DEB and Analytic Yield Spectra (AYS) Calculations of Populations for Two States From Each of the Nine Gases at Several Selected Energies

	Energy, eV	DEB	AYS	PD
Ar	100	3.23 (-2)*	3.28 (-2)	-1.5
5s _{3/2} (14.1)	1000	2.99 (-1)	3.08 (-1)	-3.0
	10000	2.99	3.02	-1.0
Ar	100	8.37 (-1)	8.42 (-1)	-0.6
Forbidden component (13.0)	1000	6.32	5.91	+6.5
	10000	5.91 (+1)	5.57 (+1)	+5.8
H ₂	100	9.12 (-1)	8.93 (-1)	+2.1
B ¹ Σ _u (Lyman) (13.013)	1000	8.74	9.06	-3.7
	10000	9.12 (+1)	9.28 (+1)	-1.8
H ₂	100	1.87 (-4)	1.89 (-4)	-1.1
³ Σ _g ⁺ (4σσ) (14.5)	1000	1.00 (-3)	1.02 (-3)	-2.0
	10000	8.74 (-3)	9.14 (-3)	-4.6
H ₂ O	100	1.00	1.07	-7.0
Dissociation continuum (7.4)	1000	8.41	9.06	-7.7
	10000	8.31 (+1)	9.08 (+1)	-9.3
H ₂ O	100	4.32	4.30	+0.5
(A ₁)ν ₁ (0.453)	1000	3.77 (+1)	4.37 (+1)	-15.9
	10000	4.73 (+2)	4.47 (+2)	+5.5
O ₂	100	4.82 (-2)	4.70 (-2)	+2.5
B ² Σ _g ⁻ (n = 3) Rydberg (16.9)	1000	4.72 (-1)	4.74 (-1)	-0.4
	10000	4.93	4.86	+1.4
O ₂	100	3.14	2.76	12.1
A ³ Σ _u ⁺ (4.5)	1000	2.69 (+1)	2.50 (+1)	+7.1
	10000	2.42 (+2)	2.43 (+2)	-0.4
N ₂	100	5.23 (-1)	5.17 (-1)	+1.1
b ¹ Π _u (12.8)	1000	4.52	4.54	-0.4
	10000	4.72 (+1)	4.62 (+1)	+2.1
N ₂	100	5.88 (-1)	5.77 (-1)	+1.9
B ³ Π _g (first positive) (7.35)	1000	4.99	4.88	+2.2
	10000	4.46 (+1)	4.80 (+1)	-7.6
O	100	9.31 (-2)	9.56 (-2)	-2.7
(⁴ S°)3d ⁵ D° (12.1)	1000	7.95 (-1)	7.79 (-1)	+5.0
	10000	7.88	7.57	+3.9
O	100	7.96	7.69	+3.4
2p ⁴ ¹ D (1.85)	1000	7.48 (+1)	7.75 (+1)	-3.6
	10000	7.56 (+2)	8.08 (+2)	-6.9
CO	100	1.41 (-2)	1.29 (-2)	+8.5
(L 2) (n = 5) Rydberg (15.96)	1000	1.38 (-1)	1.36 (-1)	+1.4
	10000	1.62	1.55	+4.3
CO	100	1.16	1.01	+12.9
a' ³ Σ ⁺ (6.91)	1000	9.15	7.98	+12.8
	10000	8.63 (+1)	7.78 (+1)	+9.8
CO ₂	100	1.84 (-2)	1.76 (-2)	+4.3
17.8-eV level (17.8)	1000	1.74 (-1)	1.77 (-1)	-1.7
	10000	1.80	1.84	-2.2
CO ₂	100	4.33 (-3)	4.23 (-3)	+2.3
C I (1561) (24.5)	1000	4.22 (-2)	4.28 (-2)	-1.4
	10000	3.52 (-1)	3.62 (-1)	-2.8
He	100	5.86 (-1)	5.38 (-1)	+8.2
2 ¹ P (21.22)	1000	5.90	6.00	-1.7
	10000	6.13 (+1)	6.23 (+1)	-1.6
He	100	1.53 (-2)	1.52 (-2)	+0.7
n > 4 ³ P (23.91)	1000	8.12 (-2)	8.40 (-2)	-3.4
	10000	7.54 (-1)	7.48 (-1)	+0.8

The percentage difference (PD) is found by $PD = [(DEB - AYS)/DEB] \times 100$. The name of the state studied is given with its threshold in parentheses (in electron volts).

*Read 3.23 (-2) as 3.23×10^{-2}

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